Fátima Lima, Manuel Lopes Nunes, Jorge Cunha, André F.P. Lucena, A cross-country assessment of energy-related CO2 emissions: An extended Kaya Index Decomposition Approach, *Energy, Volume 115, Part 2, 15 November 2016, Pages 1361-1374, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2016.05.037. (http://www.sciencedirect.com/science/article/pii/S0360544216306478)*

A Cross-Country Assessment of Energy-Related CO_2 Emissions: An Extended Kaya Index Decomposition Approach

Fátima Lima[1], Manuel Lopes Nunes[2], Jorge Cunha[2*] and André F. P. Lucena[3]

[1] Department of Production and Systems, University of Minho, Portugal
[2] Algoritmi Research Centre, University of Minho, Portugal
[3] Energy Planning Program, Universidade Federal do Rio de Janeiro, Brazil

* Corresponding author: jscunha@dps.uminho.pt, University of Minho

KEYWORDS
Carbon Dioxide Emissions, Decomposition Approach, Kaya Identity, Sustainable Development

Abstract

As the threat of climate change becomes increasingly acknowledged, it becomes more evident that past and current unsustainable energy consumption patterns cannot be pursued or maintained. In order to help policy makers across the globe to address this challenging goal, decomposition techniques have been applied to identify the main drivers of changes in energy consumption and CO_2 emissions. This study presents a cross-country assessment of main energy- related CO_2 emission drivers for Portugal, United Kingdom, Brazil and China, resorting to an approach that differentiates the contribution of all fuel alternatives – both renewable and non-renewable, including nuclear energy. The results obtained have shown the relevance of energy intensity and affluence effects as well as RES contribution as main emission drivers which means that their relationships constitute areas that require a more immediate action by energy policy decision-makers. In terms of policy implications, it seems clear that Brazil and Portugal need to focus on measures improving energy efficiency whereas China and UK need to prioritize issues regarding the weight of non-renewable energy sources in their energy mix. Another important implication is the need to promote synergies within the energy sector, regarding energy security, climate change and pollution mitigation goals.

1. Introduction

Energy's role to attain socio-economic development has been already historically recognized (see [1], [2]). Notwithstanding, as the threat of climate change becomes increasingly acknowledged, past and current unsustainable energy consumption patterns cannot be maintained. These patterns present an excessive reliance on non-renewable energy sources, with fossil fuels accounting for 87% of primary energy supply, from which 33% of oil is allocated to transport sector, and 30% of coal to electricity and industry sectors, although natural gas (24%) is increasing its share across aforementioned sectors [3]. These statistics corroborate the perspective of considering these three sectors (energy, industry and transport) as major contributors to global CO_2 emissions [4]. According to the United Nations Intergovernmental Panel on Climate Change [5] latest estimates, greenhouse gas (GHG) emissions have increased between 2000 and 2010, due mainly to energy supply (47%), industry (30%), transport (11%) and buildings (3%) sectors. Furthermore, as countries improve their socioeconomic welfare, increasing levels of goods and services production often imply increasing energy consumption and CO_2 emissions [3], [6], conditioning future energy sustainability. Therefore, accounting for energy- related CO_2 emissions becomes imperative to promote a shift towards sustainable development.

Within this context, two methodologies have been increasingly used to identify the main drivers underlying changes in energy use and CO_2 emissions. The first methodology, Kaya Identity [7], has been adopted by several institutions, such as the International Energy Agency [8], to ascertain to what extent different factors impact CO_2 emission level and has been recently extended to account for not only the impact of RES but also of nuclear energy [9]. The second methodology, Index Decomposition Analysis (IDA), although having been used in the energy sector for several decades, only recently extended its scope to environmental aspects [10], [11]. This methodology decomposes the changes in the level of CO_2 emissions into five main explanatory effects, namely activity, structure, intensity, energy mix and emission factor. Although both these techniques have been widely used at national [12]–[16] and international level [13], [17]–[19], recently developed "extended" Kaya Identity decomposition has not been previously applied in a cross-country comparison for Portugal, United Kingdom, Brazil and China.

Therefore, this work aims to promote, for this set of countries, a cross-country assessment of main energy- related CO_2 emission drivers, resorting to an approach that differentiates the contribution of RES and nuclear energy for overall carbon emissions. This set of countries is characterized by substantially different energy matrix, as well as socioeconomic backgrounds and shared responsibilities towards climate change. While developed countries have an "historic responsibility" regarding carbon emissions, emerging countries have become key players regarding future emissions, surpassing overall emissions of developed countries [20]. Furthermore, the Lisbon Treaty, signed in Portugal in 2007, has changed the energy policy landscape in the European Union (EU), establishing four main common lines of action: ensuring energy security of supply, promotion of energy efficiency, energy saving and development of RES [21], requiring coordination of energy planning at national level with transnational interests and/or goals. Moreover, increasing relevance and interconnectivity with other policy areas, such as climate change and environment has also been recognized [21], reinforcing transversal nature of this issue. It is in this context of transition between a more closed towards a more opened and shared energy planning process, willingly recognizing the relevance of energy and its interconnectivity to other key goals of sustainability that this study takes place. Regarding the chosen countries, Brazil's energy matrix includes nuclear and is mostly of a renewable nature, Portugal does not include nuclear, but has a higher share of RES than United Kingdom and China energy mix, which includes nuclear but has a lower share of RES. It is growingly recognized that the evolution of the energy sector and related policies and the ever increasing concerns with sustainable development (where the economic, environmental and social dimensions must be taken into account) have brought about profound changes regarding the energy decision-making process and the setting of a country's main goals. In this context, the analysis of the four countries included in this study, with previously mentioned different characteristics, helps to understand that sustainable energy planning should now be seen as a multidimensional process, across different scales of analysis and capable of moving from the local to the global level.

To give some perspective on the countries under analysis, the evolution of Total Primary Energy Supply (TPES), energy-related CO_2 emissions, Gross Domestic Product in Purchasing Power Parities (GDP PPP) and Population (POP) growth, for the period 1990-2010, is presented in Figure 1. As can be seen, differences in the evolution of those variables are found reflecting different socioeconomic and environmental contexts. The assessment of those indicators allows emphasizing common and diverging trends, regarding energy-economy and environment dynamics. Two common trends can be observed for all countries: the convergence between energy and CO_2 emissions as opposed to divergence between CO_2 emissions and population growth. Hence, population by itself might not promote an accurate assessment of energy-socioeconomic-emission nexus. It is also noteworthy that, to different extents, energy and carbon emissions trends both reflect fluctuations in economic growth, being coincident with expansion and recession episodes. These convergences are expected trends, given that energy sector has been considered one of the most carbon intensive human activities, albeit a crucial factor to promote economic development [8].

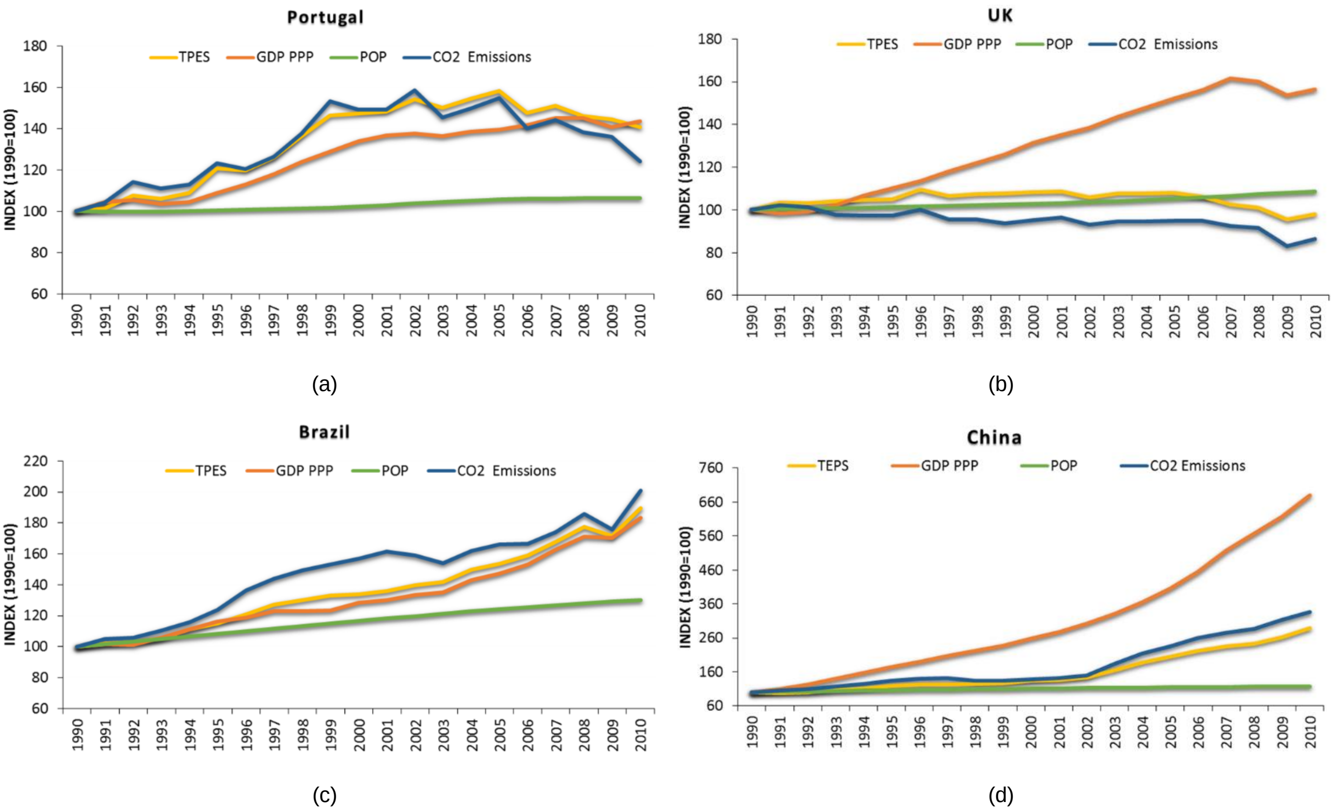

Fig. 1. Primary Energy, Population, GDP PPP and CO_2 Emissions trends[1] (Sources: [22] and [23])

As illustrated in Panel a) of Figure 1, Portugal's GDP PPP increased during the 1990s, being followed by economic stagnation until 2005. After a slight increase, this trend has been disrupted by economic recession started in year 2008. Energy use and CO_2 emissions trend have increased until 2005, registering a decreasing trend onwards. However, CO_2 emissions in 2010 were still 24% higher than in 1990. Additionally, population growth has not changed significantly comparatively to base year (1990), increasing slightly between 1990 and 2010 (6%). For the United Kingdom (UK), GDP PPP presents an increasing trend, only disrupted by the economic crises started in 2008, while both energy use and CO_2

[1] All non-energy purposes are excluded from CO_2 statistics. Therefore Land Use, Land Use Change and Forestry (LULUFC) are not taken into account in this approach.

emissions trends have gradually decreased (Figure 1, Panel (b)). This suggests a detachment between energy use, carbon emissions and GDP. Population presents a slight increasing trend during this period (being 9% higher in 2010 than in 1990).

Regarding emerging countries, although Brazil presents an increasing trend for all variables (Figure 1, Panel (c)), it is clear that the growth in CO_2 emissions was higher than that for energy use and GDP, which seems to indicate that there was not a decoupling between economic growth and its environmental impacts. For China there was an increasing trend for GDP PPP, TEPS and CO_2. However, the economic growth was more accentuated than the increase in energy use and CO_2 emissions which is indicative of a decrease in the country's energy and carbon intensities.

Overall, for the period 1990-2010, one can conclude that: a) both China and Brazil have experienced significant economic growth, with increases in GDP PPP of 580% and 83% respectively, contrasting with UK (56%) and Portugal's (43%) growth; b) both emerging countries present an important increase in energy use and energy- related CO_2 emissions; c) these emissions seem to follow closely the energy use pattern and economic growth (with the exception of UK); and d) population has kept a stable trend, without marked variations across the four countries. The use of aggregate indicators though useful to contextualize the socioeconomic and environmental background of the analysed countries, imply that identified trends and potential inter-linkages as well as their relevance is ascertained through the use of decomposition approach.

After this introductory section, the next section presents a brief overview of the literature on decomposition of energy-related CO_2 emissions. Section 3 describes the methodology adopted and data sources used. Section 4 presents the results of the decomposition approach adopted whereas Section 5 discusses those results. Finally, section 6 draws the main conclusions and presents avenues for future research.

2. Brief Literature Review

The decomposition approach has been an extensively used tool for the assessment of the energy-environment nexus (see [11], [24]) , whose emergence has reflected the increasing relevance and integration of climate change issues in energy planning (see [25], [26]). This relationship is patent in prior studies, either at country or cross-country level, often focusing different energy and carbon intensive sectors of both developed and emerging countries. For instance, the key role played by the industry sector for energy and energy- related CO_2 emission growth in China has been emphasised by [27], [28]. For both studies, focusing a similar time series, it was found that changes in aggregate carbon emissions have been driven mainly by the activity effect regarding emissions increase, in contrast to energy intensity considered the main driver for emissions decrease. Additionally, the contribution of carbon intensity nature of the energy mix for emissions increase [28], and the shift towards a cleaner energy mix towards emission decrease [27] has also been acknowledged. In spite of this, [12] claim that the impact of industry structure on emission increase has shifted recently, which has led them to suggest a coordinated decrease of intensity and structural effects to ensure emission reduction. Similarly activity effect, as well as population growth, seem to have driven emissions upwards in Brazil, between 1970 and 2009, being offset by increasing diversification of the energy mix, instead of energy intensity effect [29], [30]. In line with these studies, is the comparison between the determinants of CO_2 emissions for Brazil and Russia, from 1992 to 2011, developed by [31] that has hinted the need to further focus the "neglected" intensity effect at energy planning and environmental sustainability levels. Meanwhile, increases in energy use in industrial and residential sectors, in Brazil between 1970 and 1996, have been attributed to changes in affluence and population effects, being opposed by intensity effect [32]. Decomposition analysis of United Kingdom's manufacturing sector, performed by [33], between 1990 and 2007, has emphasised the intensity effect as the main driver for emissions amongst changes in output, industrial structure, fuel mix and electricity emission factor contributions. In the case of Portugal, decomposition of 36 economic sectors, between 1996 and 2009, has been undertaken by [16], evidencing the key role played by intensity effect. Furthermore, changes in carbon dioxide emissions at European Union (EU) level for the power sector, between 2001 and 2010 have been assessed by [34], having highlighted the contribution of intensity effect, though with opposing directions at country level, i.e. favouring emission reductions for Portugal and emission increase for United Kingdom. More recently, [35] assessment of emission drivers for electricity generation in EU-28 placed particular emphasis on the economic crisis, having shown that despite economic recession and taking into consideration Kyoto Protocol targets, intensity effect was the main driver for emission reduction offsetting increases prompted by activity effect. Additionally, crucial role played by intensity effect has also been focused in studies featuring both developed and emerging countries. For example, Kaivo-oja et. al. [18] have reported the existence of convergence regarding intensity effect towards CO_2 emission reduction in contrast to divergences of structural effect, between three major world economies (China, EU-27 and United States of America (USA)).

3. Data and Decomposition Approach

This study follows the approach proposed by [9]. As illustrated in Figure 2, it results from the combination of two major research streams: Kaya [7] and Logarithmic Mean Divisia Index (LMDI) approach [36]. These frameworks have contributed to expose inter-linkages between CO_2 emissions and anthropogenic intervention.

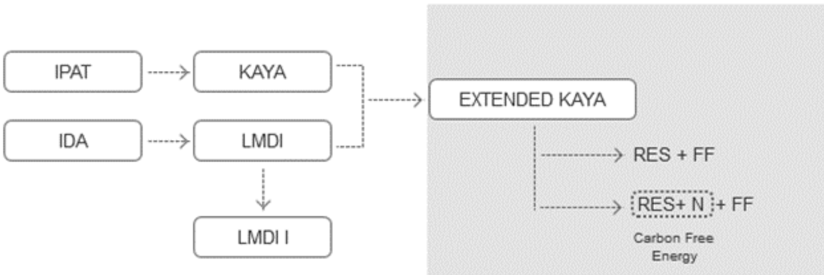

Fig. 2. Methodological Framework Design

The concept behind IPAT equation (1) has been developed by [37] and [38]. It correlates environmental impacts, I, with three factors in a simplified manner (population, P, affluence, A, and technology, T), becoming increasingly popular [20], [39]. If perceived within a sustainability framework, it can establish inter-linkages between environmental and socioeconomic dimensions [9] as indicators to measure environmental impacts of human activity [9], [20], [40], [41], as summarized in the following equation:

$$Impact\ (I) = Population\ (P) * Affluence\ (A) * Technology\ (T) \quad (1)$$

As a derivation of IPAT equation, Kaya identity [7] extends this principle to GHG emissions, promoting the assessment of drivers of energy- related CO_2 emissions [40], [42], according to:

$$CO_2 \text{ Emissions} = \underbrace{Population}_{Population} * \underbrace{(GDP/Pop)}_{Affluence} * \underbrace{(Energy/GDP) * (CO_2/Energy)}_{Technology} \quad (2)$$

Besides population and affluence, this approach takes into consideration additional influencing factors regarding overall emissions, such as energy intensity of economy (energy/GDP) and carbon intensity of energy (CO_2/energy). Despite this, Kaya identity maintains IPAT's straightforward structure, featuring three original impact determinants, as illustrated in equation (2). In recent years, Kaya identity has been extended (e.g. [41], [42]) in order to account not only for the contribution of fossil fuel (FF), but also for renewable energy sources (RES), as emphasised in Figure 2. Notwithstanding, equation (2) does not differentiate between the contribution of RES and other carbon-free alternatives (e.g. nuclear energy (N)), which has led [9] to develop an "extended Kaya" equation to address the previously mentioned gap (see Figure 2).

The first step in this novel approach is to establish an identity function, which in this case corresponds to an adaptation of the original Kaya identity equation. As so, extended version encompasses the following effects:

$$C_{tot} = \sum_i C_i = \sum_i [(C_i/FF_i) * (FF_i/FF) * (FF/FFN) * (FFN/E) * (E/Y) * (Y/P) * P] = \sum_i F_1 S_1 S_2 S_3 IGP \quad (3)$$

Where,
C_{tot} = CO_2 emissions
C_i = CO_2 emissions from fossil fuel type *i*
$F_1 = C_i/FF_i$, CO_2 emission factor, for fossil fuel type *i*
$S_1 = FF_i/FF$, share of fossil fuel *i* in total fossil fuel
$S_2 = FF/FFN$, shares of fossil fuel in total fossil fuels plus nuclear
$S_3 = FFN/E$, share of fossil fuels plus nuclear in total energy
$I = E/Y$, aggregate energy intensity
$G = Y/P$, GDP per capita or affluence
$P =$ Population

This redefined identity function is then subject to a decomposition approach. As illustrated in Figure 2, this study has adopted an Index Decomposition Approach (IDA), which is widely used to analyse the contribution of each factor to shifts in aggregate carbon emissions, and promoting cross-country comparisons [11]. Within IDA, Logarithmic Mean Divisia Index (LMDI) has been favoured to other decomposition methods in virtue of its advantages [36], that range from perfect decomposition (no residual terms); ability to cope with zero values (replacement by small positive value, between 10^{-10} and 10^{-20}); simplified inter-linkages between additive and multiplicative version and consistency in aggregation. Inexistence of negative changes, easiness of application and interpretation have also been emphasised by [36] and [42] as desirable properties of multiplicative form. Furthermore, due to "ease of formulation" LMDI I has been the most recommended methodology by [10] and [36].

Therefore, given abovementioned properties, this study follows the multiplicative LMDI I decomposition approach to explain changes in CO_2 emissions and can be represented as illustrated bellow (Table 2 describes each one of the emissions drivers):

$$C_{tot} = \frac{C_t}{C_0} = C_{emf} C_{ffse} C_{nec} C_{rec} C_{int} C_{ypc} C_{pop} \quad (4)$$

In this equation C_{emf} stands for emission factor effect, and together with C_{int}, energy intensity effect, they constitute intensity effect; C_{ffse} represents fossil fuel substitution, contributes along with C_{rec} and C_{nec} to structural effect; C_{ypc} and C_{pop} constitute scale effects.

Table 2 – Summary of main drivers contemplated in decomposition approach (adapted from [9])

Variable	*Drivers/Effects*	*Typology*	*Significance*
C_{tot}	CO_2 emissions	Aggregate	Total change in CO_2 emissions from energy use
C_{emf}	Emission Coefficient Factor	Intensity	Changes in carbon content per unit of fossil fuel (coal, oil, gas)
C_{int}	Energy Intensity	Intensity	Changes in energy/GDP or energy intensity
C_{ffse}	Fossil Fuel Substitution	Structure	Substitution or fuel switching (coal, oil, gas) in total fossil fuels
C_{nec}	Nuclear Energy Contribution	Structure	Nuclear energy contribution by displacement of fossil fuels
C_{rec}	Renewable Energy Contribution	Structure	Renewable energy contribution by displacement of fossil fuels (hydro; wind; solar; biomass…)
C_{ypc}	Affluence	Scale	Changes in GDP/capita or affluence
C_{pop}	Population	Scale	Changes in total population

In accordance to LMDI I method (considered by [43] a simpler LMDI formulae), each one of these components can be calculated as:

$$Cemf = \exp\left[\sum_i wi * \ln\left(\frac{F_1^t}{F_1^0}\right)\right] = \exp\left[\sum_i \frac{(C_i^t - C_i^0)/(lnC_i^t - lnC_i^0)}{(C^t - C^0)/(lnC^t - lnC^0)} * \ln(F_1^t/F_1^0)\right] \quad (5)$$

$$Cffse = \exp\left[\sum_i wi * \ln\left(\frac{S_1^t}{S_1^0}\right)\right] = \exp\left[\sum_i \frac{(C_i^t - C_i^0)/(lnC_i^t - lnC_i^0)}{(C^t - C^0)/(lnC^t - lnC^0)} * \ln(S_1^t/S_1^0)\right] \quad (6)$$

$$Cnec = \exp\left[\sum_i wi * \ln\left(\frac{S_2^t}{S_2^0}\right)\right] = \exp\left[\sum_i \frac{(C_i^t - C_i^0)/(lnC_i^t - lnC_i^0)}{(C^t - C^0)/(lnC^t - lnC^0)} * \ln(S_2^t/S_2^0)\right] \quad (7)$$

$$Crec = \exp\left[\sum_i wi * \ln\left(\frac{S_3^t}{S_3^0}\right)\right] = \exp\left[\sum_i \frac{(C_i^t - C_i^0)/(lnC_i^t - lnC_i^0)}{(C^t - C^0)/(lnC^t - lnC^0)} * \ln(S_3^t/S_3^0)\right] \quad (8)$$

$$Cint = \exp\left[\sum_i wi * \ln\left(\frac{I^t}{I^0}\right)\right] = \exp\left[\sum_i \frac{(C_i^t - C_i^0)/(lnC_i^t - lnC_i^0)}{(C^t - C^0)/(lnC^t - lnC^0)} * \ln(\frac{I^t}{I^0})\right] \quad (9)$$

$$Cypc = \exp\left[\sum_i wi * \ln\left(\frac{G^t}{G^0}\right)\right] = \exp\left[\sum_i \frac{(C_i^t - C_i^0)/(lnC_i^t - lnC_i^0)}{(C^t - C^0)/(lnC^t - lnC^0)} * \ln(\frac{G^t}{G^0})\right] \quad (10)$$

$$Cpop = \exp\left[\sum_i wi * \ln\left(\frac{P^t}{P^0}\right)\right] = \exp\left[\sum_i \frac{(C_i^t - C_i^0)/(lnC_i^t - lnC_i^0)}{(C^t - C^0)/(lnC^t - lnC^0)} * \ln(\frac{P^t}{P^0})\right] \quad (11)$$

Where w_i represents the weight function, each one of these equations represents a factor that contributes to a change in total CO_2 emissions, during a stipulated timeframe t (with t = 1990, …, 2010 in this study).

Regarding the decomposition approach undertaken, given that this study's database covers a large dataset, from multiple countries in a consistent manner and over a considerable period of time, an annual chaining perspective was adopted, similarly to [41], [44]. Furthermore, lack of accessibility to a more detailed emission database has rendered impossible the initial intention of assessing emissions at sectorial level. Notwithstanding, the use of primary energy has its advantages, allowing to portray improvements from the supply side that would otherwise pass unnoticed from a final consumption perspective [3]. For empirical analysis, a database was built from a combination of two main data sources: the International Energy Agency (IEA), for primary energy and energy- related CO_2 emissions; and the World Development Indicators series (World Bank), for population and GDP. Furthermore, by using GDP expressed in Purchasing Power Parities (PPP) at constant prices for 2005, this study avoids distortions in energy intensity values by disregarding differences amongst countries prices [3], [45]. Both primary energy and CO_2 emissions data contemplate fossil fuel contributions (coal, oil and natural gas) and has been assembled in internationally standardized World Bank database. Although a detailed level of information has been considered crucial to provide a comprehensive policy assessment, intensity effect has often been measured at aggregate level given limited availability and quality of disaggregate databases (see [3], [46]). However, efforts have been developed by several international organizations and projects (e.g. IEA and ODYSSEE-MURE Project) to overcome this shortcoming and improve data gaps at sectorial and sub-sectorial levels ([3]). Another drawback associated with the decomposition approach is increasing complexity of result interpretation and analysis brought by interconnectivity and interdependency amongst effects (see [47], [48]). This affinity is expected to increase with the number of variables considered in decomposition equation [48], but could be surpassed resorting to an econometric approach to determine what kind of causality is associated with these complementary effects [47]. Additionally, the need to take into account differing socioeconomic and environmental contexts, still makes cross-country assessment a challenge [49], even though the current work is reflective of data and decomposition choices that look to improve methodological issues and promote effective cross-country comparisons, as suggested by [50], [51].

4. Decomposition results

Results from annual chaining decomposition, between 1990 and 2010, are summarized in this section (Tables with detailed values for all energy- related CO_2 emissions drivers for all countries are presented in Appendix A). Following [45], a classification criteria was adopted, in order to facilitate the interpretation of results regarding the impact of the different CO_2 emissions drivers. It consists of a three level criteria where a value of 1.00 means no change in emissions; a value below 1.00 means that a particular driver has contributed to a reduction in emissions, whereas a value above 1.00 implies an increase in emissions.

Figure 3 shows the cumulative change in CO_2 emissions (Ctot) as well as in the respective driving forces for Portugal since 1990 until 2010. As expected, Ctot is above 1 almost for all years until 2005 and below 1.00 afterwards. Energy intensity (Cint), affluence (Cypc) and contribution of renewables (Crec) seem to play a key role regarding carbon emissions in Portugal.

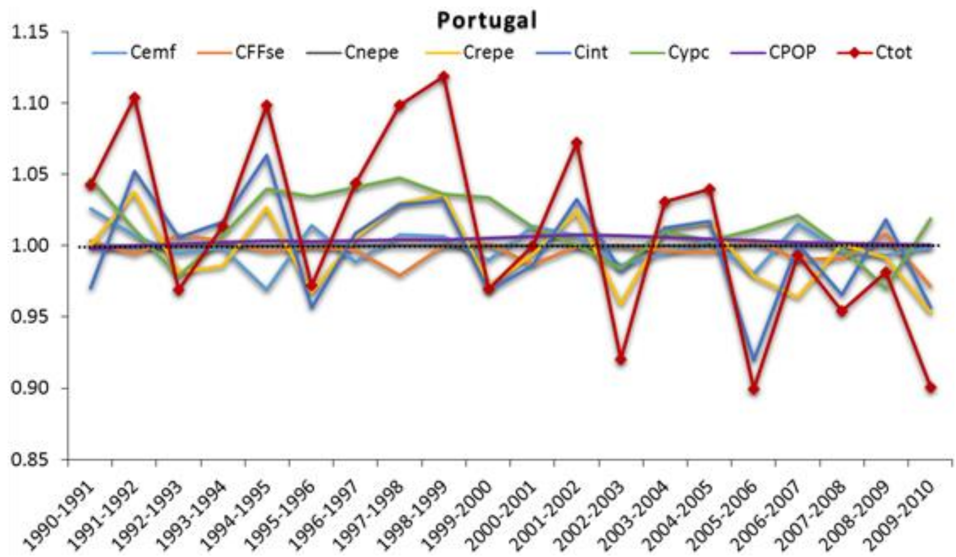

Fig. 3. Cumulative decomposition of CO_2 emissions in Portugal (Source: authors elaboration from data on [22] and [23]).

Higher increases in carbon emissions occurred during the 1990s and the main drivers were energy intensity (Cint), and affluence (Cypc) effects, implying a shift towards more energy and carbon intensive economic activity structure and energy mix, along with a greater GDP per capita. During this period, these factors were opposed by fossil fuel substitution effect (Cffse), implying that primary energy mix underwent a shift towards less carbon intensive alternatives. This factor has contributed to slowdown rising emission levels for this period. The reduction in carbon emissions in 2000's decade (especially from 2005 onwards) is explained mainly by the effect of energy intensity (Cint), fossil fuel substitution (Cffse) and contribution of renewables (Crec) that have outweighed the impact of the affluence effect (Cypc). As expected, population growth (Cpop) has not been an influencing factor for CO_2 emission growth during the entire period of analysis.

Since UK's CO_2 emissions presented a decreasing trend for the period analysed, Ctot is almost always below 1.00 as illustrated in Figure 4. From this Figure, it is clear that energy intensity (Cint) was the main driver of decline on total CO_2 emissions. Also, fossil fuel substitution effect (Cffse) has had a positive impact for the decline on carbon emissions. On the contrary, contributing for the increase in aggregate CO_2 emissions was the affluence effect (Cypc) since its value is almost always clearly above 1.00. However, it seems that the magnitude of the impact of energy intensity and fossil fuel substitution surpassed that of the affluence effect therefore contributing to achieve decoupling between emissions and economic growth. The other four drivers (Cemf, Cnepe, Crepe, and Cpop) have had a marginal impact either on increasing or decreasing energy- related CO_2 emissions.

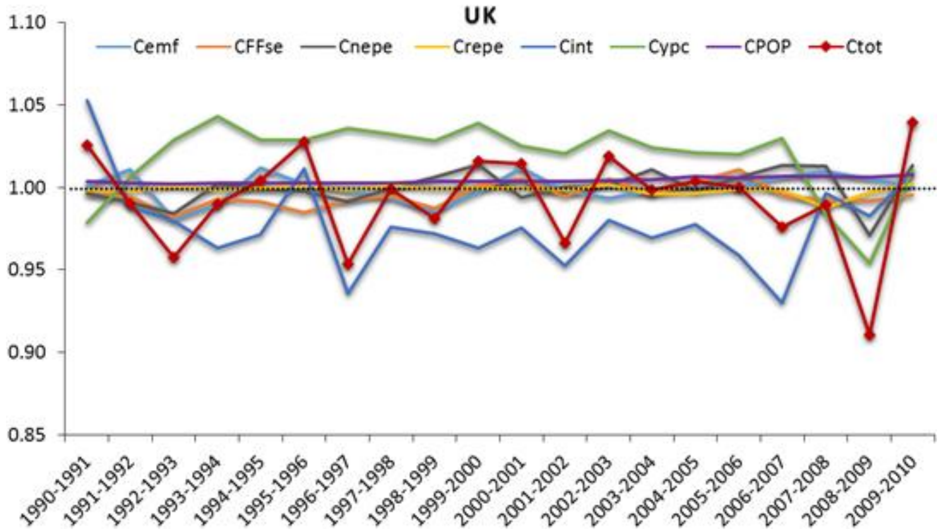

Fig. 4. Cumulative decomposition of CO_2 emissions in UK (Source: authors elaboration from data on [22] and [23]).

As Brazil has shown an increasing trend for energy- related CO_2 emissions, the Ctot variable in Figure 5 is always above 1.00 (with only three years as exception). The main drivers of that increase in carbon emissions were energy intensity (Cint), the affluence effect (Cypc), and population growth (Cpop) for the entire period of time. For the 1990's decade the influence of renewables (Crec) has also contributed for an increase in CO_2 emissions, with a reversal of this impact in 2000's decade. The emission factor effect (Cemf) and contribution of nuclear effect (Cnec) have had no impact on carbon emissions, since their value were almost always equal to 1.00. Therefore, it seems that the Brazilian economic and population growth have driven to steep increases of energy use and carbon emissions that were not offset by an improved energy efficiency of the country (reflected in the Cint variable).

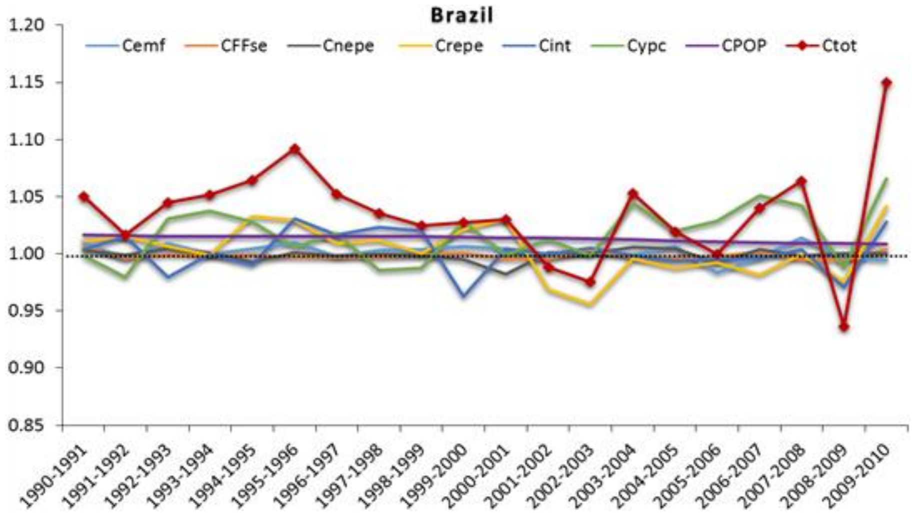

Fig. 5. Cumulative decomposition of CO_2 emissions in Brazil (Source: authors elaboration from data on [22] and [23]).

Similarly to Brazil, China has witnessed an important increase on energy- related CO_2 emissions, particularly from 2001 onwards, and this trend is reflected in Figure 6 by the fact variable Ctot being always above 1.00. From Figure 6, it is possible to see that the main factor contributing for the increase on carbon emissions was the affluence effect (Cypc), derived from the important economic growth of China in this period. The role of renewables (Crepe) and, to a less extent, of population growth (Cpop) have also contributed to an increase in carbon emissions. Counterbalancing this increase was, mainly, an increase of energy efficiency on China's economy, since variable Cint is almost always below 1.00. Additionally, the emission coefficient factor (Cemf) has had some impact on reducing energy- related CO_2 emissions. From the analysis of Figure 6, is also possible to identify three periods that show important annual changes in CO_2 emissions. The first corresponds to 1994-1995 where the affluence effect clearly offset the energy intensity effect leading to a significant increase in carbon emissions. The second corresponds to 1997-1998 period where an important decrease in overall carbon emissions was verified. This decrease has resulted from a combination of both energy intensity (Cint) and emission factor (Cemf) effects (i.e. efficiency rise and lower carbon content) which have been enough to offset the affluence effect. Finally, the period 2001-2005 witnessed a significant annual increase in aggregate CO_2 emissions, where most of the effects featured in this decomposition approach (with the exception of fossil fuel substitution (Cffse) and contribution of nuclear effect (Cnec)) have contributed to that increase.

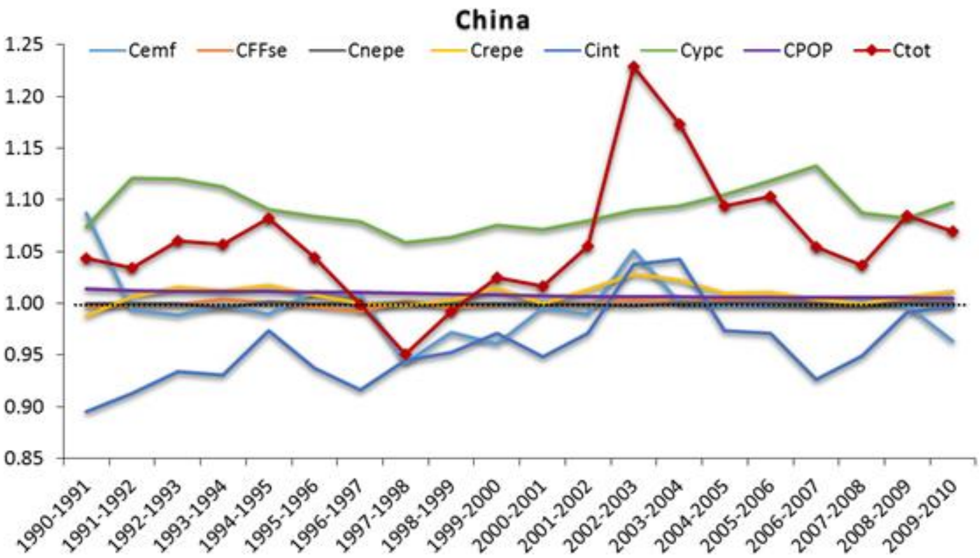

Fig. 6. Cumulative decomposition of CO_2 emissions in China (Source: authors elaboration from data on [22] and [23]).

Summarizing, decomposition results have emphasised the relevance of energy intensity (Cint), affluence (Cypc) and, to a less extent, renewable energy contribution (Crec) effects. Their combination has contributed to increase carbon emissions (Ctot) in developed and emerging countries. Though affluence effect (Cypc) has been considered the main driver for carbon emission peaks, other common factors have contributed to increase overall emissions, namely increasing energy intensity and decreasing contribution of renewables effect (with the exception of UK). Similarly, though reductions in energy intensity (Cint) have consistently contributed to reach most accentuated decreases, decomposition results have also highlighted contribution of other factors such as reductions in affluence (with the exception of China) and increasing contribution of renewable energy, whereas remaining effects have played a less significant role comparatively to main divers (Cint and Cypc). Despite prevalence of years with total effect (Ctot) above 1.00 between 1990 and 2010 (Figures 3-6), decomposition results have also evidenced episodes of decoupling between economic growth and energy- related carbon emissions (Ctot) for most countries (with the exception of Portugal). These episodes have also been driven by a common effect to all countries, energy intensity (Cint) reductions, which, combined with other drivers exposed by extended Kaya, have contributed to offset affluence effect. Therefore, given heterogeneity of the results obtained, a more in-depth evaluation of these effects and their interconnections is provided in the next section.

5. Discussion of results

Following the classification of energy- related CO_2 emissions change drivers presented in Table 2, the cumulative decomposition results are analysed from the perspective of each type of effect in this section.

5.1 Scale Effect (Cypc and Cpop) Perspective

Decomposition results have highlighted adverse contribution of scale effects towards increasing CO_2 emission (Ctot) trend four all countries analysed, as illustrated in Figure 7.

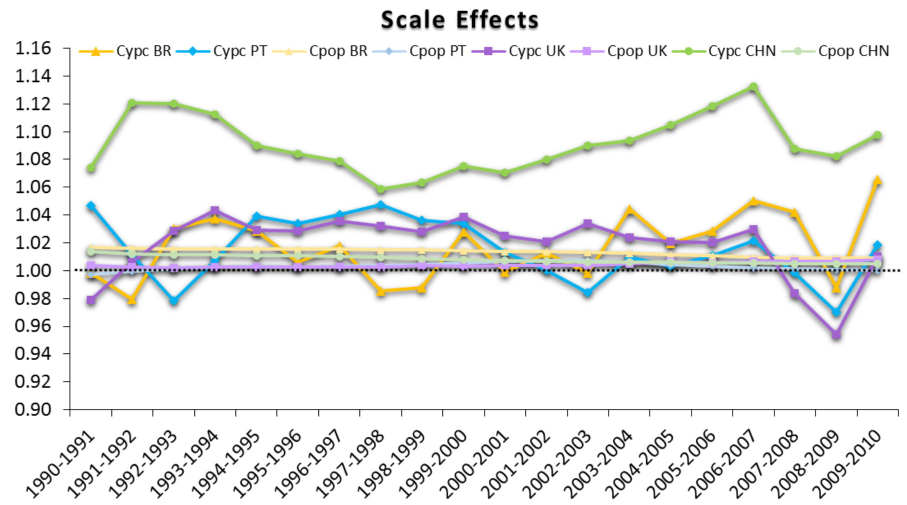

Fig. 7. Scale Effects for CO_2 Emissions Decomposition (Source: authors elaboration from data on [22] and [23])

Though both these effects have derived from decomposition of economic output (GDP PPP) [52], changes in affluence effect (GDP PPP/POP) seem to be more significant than changes in population growth (POP). Shifts in population growth rate were not significant within the timeframe considered, maintaining population effect practically unaltered, yet always above or equal to 1.00. This means that, even without significant changes, population effect was either positive (above 1.00) or neutral (equal to 1.00), never actively contributing to decrease (below 1.00) overall emissions for the set of countries. In spite of this, in emerging countries, where population growth was more significant, population effect and growth rates evidenced a slight decrease in more recent years. These results are in keeping with [29] findings for Brazil where positive contribution of this effect has been recognized in spite of minor fluctuations in recent years; and with [42] where declining population trend in China has been attributed to a strict family planning policy in vigour since 1970s. Aging population has been identified as a shaping factor for developed countries [53], contextualizing the evolution of Cpop effect and macroeconomic indicators for Portugal. In recent years, population growth rates have been reflective of low birth rates and negative net migration values, associated with economic crisis [54]. However, slight increase in both population effect and growth rates for UK in the last half of 2000's decade, has also been indicative of positive contribution of migration flux. International migration has been considered a focal aspect when considering demographic growth [18], especially in Europe where immigration in search of labour and improved quality of life has been recurrent [55]. Therefore, based on the results obtained, human-emission interactions should be increasingly focused rather than population growth by itself. This key observation is aligned with [20] perception that population effect is bound to be replaced as a determinant for CO_2 emissions, in virtue of its decreasing influence. Aspects such as mass urbanization, trade and consumption seem to be emerging as driving forces for carbon emissions. Furthermore, new approaches to emission assessment have emphasised the need to consider additional aspects, such as consumption patterns and technology when considering Cpop [40].

Given this, variations in population effect (Cpop) have had a less significant impact on emissions comparatively to affluence effect (Cypc), considered as the main driver for overall carbon emissions between 1990 and 2010. Increasing relevance of affluence in detriment of population effect has also been observed in previous studies [9], [18], [20], [42], [55], [56]. Taking into account affluence definition - and the secondary role played by population effect - its dominance seems to be mostly associated with shifts in economic growth, indirectly illustrating the relevance of this macroeconomic indicator for overall emissions. This influence is patent for all countries analysed. However, most significant impacts were verified in emerging countries, which is consistent with increasing relevance of these countries in global economy and therefore as large emitters. Both [57] and [58] have highlighted China's top position, surpassing other countries (developed or emerging) in terms of population, energy production and consumption and GHG emissions. Associated with increasing affluence emerging countries have also seen a shift in consumption patterns, converging towards developed country standards [40], which might entail considerable increases in terms of carbon emissions. Additionally, consumption preferences for "services and high value-added products" in developed countries have also contributed for relocation of heavy industries to emerging countries [17], increasing emission differential between both set of countries.

Thus, although considerable potential for emission reduction has been recognized in population and affluence effects [52], [56], most policies for emission reduction focus energy and carbon intensity since economic growth has been considered an imperative for both developed [9] and emerging countries [6]. Nonetheless, it has been increasingly recognized that in order to promote long-term climate change mitigation, regardless of developmental stage, it is imperative to raise awareness towards a more "sustainable lifestyle" [20].

5.2 Intensity Effect (Cint and Cemf) Perspective

Regarding this perspective, decomposition results have highlighted that, in general, emission factor effect (Cemf) played a less significant role than energy intensity (Cint) effect on reducing energy- related CO_2 emissions, as illustrated in Figure 8.

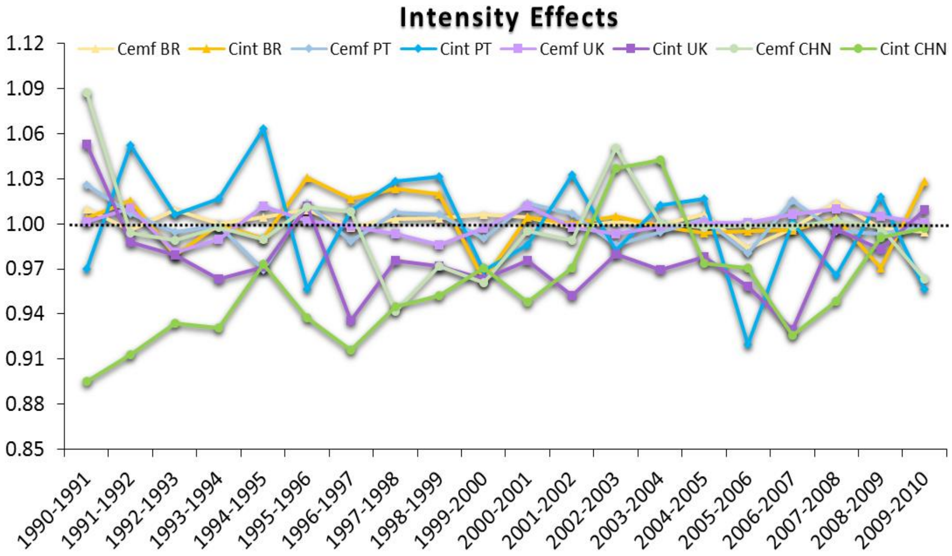

Fig. 8. Intensity Effects for CO_2 Emissions Decomposition (Source: authors elaboration from data on [22] and [23])

In spite of key role played by energy intensity effect (Cint) towards decreasing overall emissions (Ctot), most accentuated decrease was reached with the contribution of both intensity effects, though in different degrees. Carbon emission factor (Cemf) measures "changes in carbon content per unit of fossil fuel", being associated with technical aspects such as "fuel quality and potentially, abatement technologies" [9]. Carbon content of different energy alternatives influence carbon emissions, with coal being considered the most carbon intensive fossil fuel, followed by oil and natural gas, contrasting with emission free alternatives - wind, solar and nuclear power [52]. The increasingly renewable nature of the energy mix, hence lower carbon content, has contributed to either attenuate emission increase during peak emission or motivate emission decrease during most accentuated decrease. This inter-linkage between renewable energy mix and carbon emission factor effects is particularly evident within emerging countries. Although both emerging countries have seen an increase in energy use and emissions associated with economic growth, emission factor effect had a positive contribution (Cemf below 1.00) towards emission decrease in China and practically no impact on Brazil's aggregate emissions (Cemf almost always equal to 1.00). These results are reflective of carbon content of each country's energy mix. Whereas Brazil's energy supply from hydropower and sugarcane products has seen a remarkable increase [29], China's energy supply despite recent efforts to diversify its energy mix, is mostly dependent on fossil fuels, namely coal and oil as emphasised by [42] and [18]. However, natural gas has been progressively increasing its share, promoting coal's replacement [59], thus making a significant contribution to decrease carbon intensity of the energy mix. Meanwhile, although Portugal and UK have seen in recent years a positive transformation of their energy mix, Cemf behaviour during peak emissions might also be indicative of the energy system's dependence on fossil fuel alternatives, especially during economic growth periods. Such results reinforce [20] perception that, in order to ensure emission reduction during periods of economic expansion, improvements of intensity effect should also focus energy mix shifts towards renewables, reducing its carbon content. Moreover, this transition towards less carbon intensive alternatives could also be encouraged by technological improvements [17] comprised within the energy intensity effect (Cint).

This effect has diverged considerably between and amongst advanced and emerging economies. China has seen significant reductions in economy's energy intensity contrasting with Brazil. These results are in keeping with [13] findings for Brazil where despite structural shift towards "less energy intensive industries", a loss of efficiency combined with fast economic growth has led to an increase in overall emissions. Associated with upsurges in energy intensity, [29] has identified technological innovation, production chain management and energy savings as policy measures requiring further improvements in Brazil. Conversely, decreasing energy intensity has consistently opposed affluence effect in China, contributing to curb carbon emissions. Simultaneous decrease of emission factor (Cemf) and energy intensity (Cint) effects during most significant reduction is in keeping with [27] findings emphasizing that shutting down of high carbon content and low efficiency companies, have contributed to increase efficiency and decrease carbon content of the energy mix promoting a decoupling effect. Efficiency gains in China have been reached through policy efforts to reduce emissions and energy consumption, establishing energy intensity targets (see [60]). Still, high energy consumption and GDP growth rates denote industrialization and urbanization needs of an emerging economy. Therefore, the relevance of this effect for emission reduction, especially for emerging countries undergoing such a critical transition, should be reinforced [18]. While Brazil should prioritize efficiency improvements, aiming to minimize energy waste and carbon emissions, China should further improve energy and carbon intensity by shifting towards cleaner energy sources [14]. Technological improvements could play an important role in this process through the use of carbon capture and storage (CCS), favouring the use of natural gas instead of coal [42]. The use of CCS in the future would contribute to conciliate the use of coal in an increasingly emission restrictive environment [52].

In what concerns Portugal and UK, it is clear that energy intensity effect has played a more significant role in decreasing UK's CO_2 emissions than for Portugal. For some years, Portugal has seen dissociation between increasing affluence and decrease of carbon emissions. This shift between economic and emission growth is consistent with [54] assessment of the country's environmental and socio-economic context. In the last few years, emission trend has been largely defined by industry relocation and economic recession. However, [54] has emphasised that recent improvements have resulted from a combination of the following factors: a shift towards less carbon intensive alternatives, technological upgrading of energy sector through cogeneration units and combined heat and power plants, and efficiency improvements in production processes and fuel quality. Therefore, these improvements in carbon emission factor (Cemf) and energy intensity (Cint) led to an overall decrease in emissions in recent years. Moreover, this result is also reflective of policy efforts focusing energy production and consumption (see targets set by [61]).

In the case of UK, intensity effect has contributed for a decrease in aggregate CO_2 emissions due to heavy industry relocation, sectorial efficiency improvements and transition towards less energy intensive sectors. This trend has also been mentioned by [20] and [18] as a differentiating aspect between developed and developing countries. However, [62] foresees in the long-term a convergence of energy intensity trend for both set of countries. These two aspects have not conditioned strong decoupling effect between industrial growth and environmental impacts during 1990-2003 [49]. During this time frame [63] have highlighted the implementation of new technologies and facilities and a shift towards more efficient alternatives has contributed for emission reduction, in spite of increasing GDP.

Given this, current progress has resulted from a series of multi-sectorial measures to improve energy efficiency (e.g. [64]). Notwithstanding, in both developed and emerging economies besides intensity effect, emission reduction has also often implied shifts in energy mix constitution included in structural effects, evidencing interconnectivity amongst effects. Thus, development of policies promoting energy intensity improvements will have repercussions in the energy mix of a country, either promoting incorporation of RES or fossil fuel substitution either way, reducing its carbon content, ultimately promoting a shift towards less energy and carbon intensive sectors of economy [16].

5.3 Structural Effect (Crec, Cnec and Cffse) Perspective

Within structural effect, decomposition results have emphasised that fuel switching (Cffse) has had a less significant effect for both sets of countries, nuclear energy contribution (Cnec) effect has had a punctual role in reducing emissions in Brazil and UK and finally renewable energy contribution (Crec) has had a more significant role in Portugal and Brazil, although its relevance and increasing incorporation has been recognized in UK and China, as portrayed in Figure 9.

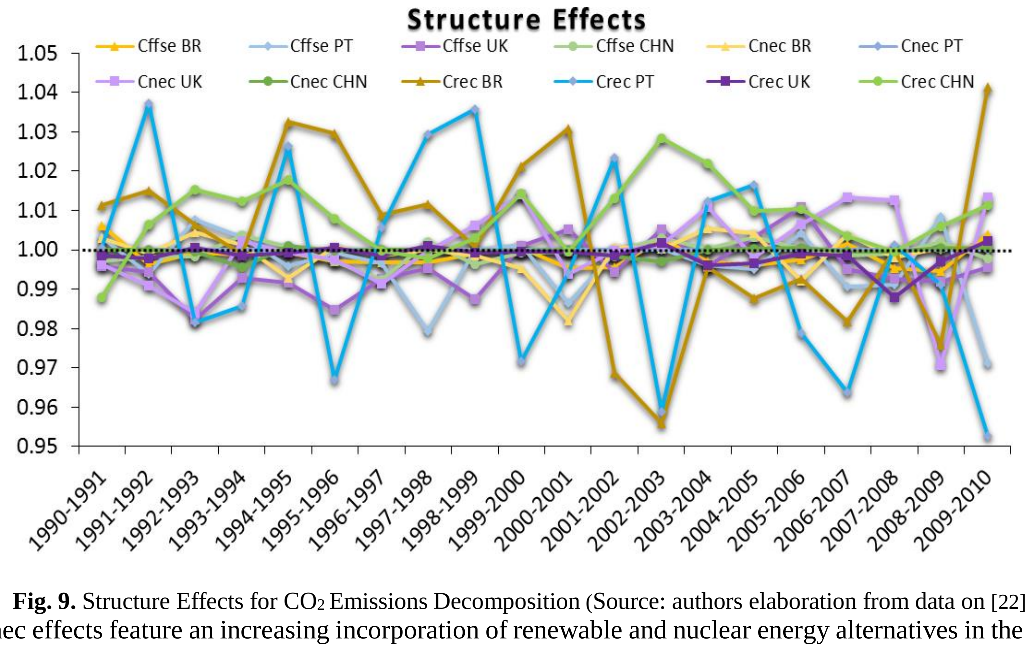

Fig. 9. Structure Effects for CO_2 Emissions Decomposition (Source: authors elaboration from data on [22] and [23])

Crec and Cnec effects feature an increasing incorporation of renewable and nuclear energy alternatives in the energy mix. Therefore implying fossil fuels displacement and implicitly altering its carbon content. Given interconnection with the emission factor effect (Cemf) main divergences regarding energy mix diversification are expected amongst emerging countries. In fact, renewable energy contribution (Crec) has played mostly opposing roles in Brazil and China. These results are once more reflective of the nature of each country's energy mix (mostly renewable for Brazil and non-renewable for China). Exceptional nature of the energy system in Brazil has contributed to a low emitting power sector contrasting with China's high emitting power sector [65]. In spite of this, Brazil has faced recently a serious energy crisis, resulting from a combination of the country's dependency on hydropower generation (over 80%) and extended lack of rainfall [66]. The need to diversify Brazilian energy matrix became an opportunity to intensify the shift towards other renewable energy sources focusing on deployment of small hydropower, biomass and wind power [30], [66]. This episode and subsequent policy effort to maintain renewable nature of the energy matrix has been captured by decomposition approach. Notwithstanding, it has also reflected susceptibility of renewable energy alternatives to climatic variations. These results are in keeping with [9] and [67] that has extended this assessment by focusing interconnection to climate change. In this context, Brazil has recently established GHG emission targets consisting of absolute reductions [68]. Interestingly, Cnec effect has had a punctual contribution in emissions reduction during the 2001 blackout episode, possibly benefiting from "Angra 2" nuclear facilities becoming commercially operational during this year [69]; while Cffse effect has kept unaltered given that natural gas has been mostly used as backup thermal power generation for electricity generation [65].

Given the accelerated rate of economic growth and nature of the Chinese energy mix, [12] have emphasised that substantial reduction in carbon emissions is a challenge in the short-term. Current struggle for emission reduction is patent in the results obtained, since components of structural effect that could contribute for emission reduction are consistently unaltered (Cffse and Cnec) or contributing to increase emissions (Crec). Nevertheless, [42] have considered fuel switching from coal to natural gas and fossil fuel substitution by nuclear and RES viable and desirable options to reduce carbon emissions in China. Furthermore, privileged use of coal in China has also been tied to other policy goals such as energy security [18]. It has been found that the shift towards renewables would contribute to simultaneously reduce carbon emissions while improving energy security [57], promoting convergence of policies within the energy sector. In order to reduce coal dependency, the 12th Five Year Plan established, for the period 2011-2015, a substantial increase of renewable energy technologies [60]. Despite this clear commitment, several authors [12], [27] have emphasised the need to articulate policy measures in order to conciliate economic growth and environmental concerns to attain energy sustainability. From the decomposition results obtained, it seems that only a converging approach featuring structural and intensity effects can contribute to reduce emissions without hindering economic development.

Similarly to emerging countries, fossil fuel substitution (Cffse) and nuclear energy contribution (Cnec) effects have had a less significant or null role in emission reduction in developed countries. Nonetheless, Cffse contribution to emission reduction has been noticed in Portugal during the late 1990s, due to natural gas introduction in national energy matrix, circa 1997 [54]. [33] claim UK experienced a similar phenomenon during the 1990s, with increasing use of natural gas for electricity generation, known as "dash for gas" episode. While null contribution from nuclear energy has been expected for Portugal given its absence from the energy matrix, in UK this effect has contributed punctually to attenuate increase of overall emissions. Currently, nuclear share for electricity generation is only slightly higher (20%) than contribution of total renewable energy share (19%) [70], with future plans for expansion for both alternatives. However, at international level, recent evolution of this low carbon alternative has been stalled by uncertainty brought on by Fukushima incident in Japan [71]. Therefore, taking into account the decomposition results obtained, further debate regarding the future of nuclear energy should be undertaken.

Conversely, increasing RES contribution (Crec) has been evidenced during this period, however with different impacts for Portugal and UK. For Portugal, relevance of carbon free alternatives has increased considerably between 2004 and 2009, especially regarding installed capacity of wind power projects [72]. Displacement of fossil fuels by renewable energy and subsequent contribution to mitigate CO_2 emissions during this period has been observed in the results obtained. In spite of this, it has been found that intermittency associated with increasing RES deployment can contribute to amplify emissions instead of mitigating them. Similarly to Brazil, in dryer years, hydropower generation decreases its contribution for electricity generation, contributing to increase carbon emissions. An additional issue relates to the relevance of renewable energy alternatives to ensure national energy security (by reducing foreign energy dependency) and to improve the balance of payments account (given the burden fossil fuel imports still have in the Portuguese economy). Portugal has seen in recent years increasing diversification towards a cleaner energy matrix, promoting greater incorporation of wind power, solar and biomass for electricity generation. According to [9], this approach would contribute, to a certain extent, to enhance Crec effect by reducing the share of hydropower generation. Thus, this result exposes simultaneously main advantages and disadvantages from RES deployment. If, on the one hand, a greater CO_2 emission reduction is promoted, on the other hand, uncertainty of energy supply is increased.

Although UK has seen its share of renewables for electricity generation triplicate between 2000 and 2012, fossil fuels still account for the bulk of the country's energy consumption (from which 37% oil and 33% natural gas) [70]. Minor contribution of Crec effect reflects to a large extent the energy mix constitution. Therefore, as observed in the decomposition results obtained, carbon emission reduction has resulted mainly from energy efficiency improvements. Albeit, contribution from structural effects has been crucial for emission reduction in recent years, having resulted from policy efforts to improve energy security and decarbonize economy [70]. Similarly to Portugal, UK has adopted absolute pledges that have a legally binding nature (see [71], [73]). Decomposition results and policy efforts are also indicative that further improvements in overall emissions require complementary measures featuring structural and intensity effects.

To sum up, diversification of the energy mix towards a cleaner (low carbon content) alternative has been considered crucial to attenuate overall carbon emissions regardless of developmental stage. Nevertheless, as previously emphasised, in order to promote a greater emission reduction that enables target fulfilment, measures featuring affluence, structural and intensity effects need to be aligned.

6. Conclusions

As the threat of climate change becomes increasingly acknowledged, it becomes more evident that past and current unsustainable energy consumption patterns cannot be pursued or maintained. However, G20 economies have recently agreed to address together climate change issues while pursuing economic growth [20]. Within this context, in order to promote policy action towards energy sustainability, this study has developed an extended decomposition approach. This method has enabled to identify key drivers for CO_2 emissions, accounting for the contribution of all fuel alternatives – both renewable and non-renewable, including nuclear energy. Based on this approach, a cross-country comparison was developed highlighting main common and diverging drivers associated with emission trends.

The results obtained put in evidence that energy intensity and affluence effects have been the major drivers of changes in energy- related CO_2 emissions for all countries analysed, even though yearly trends diverge considerably amongst countries. Overall carbon emissions tend to follow closely energy intensity effect, being more clearly opposed by affluence effect in UK and China comparatively to Portugal and Brazil. Although there have been episodes, at a country level, where both those effects have contributed to increase carbon emissions, decrease of overall emissions has been promoted mainly by energy intensity effect whereas affluence effect has contributed mostly towards emission increase. Also, affluence effect seems to be more significant at a yearly basis than changes in population growth for all countries. Renewable energy contribution effect has been clearly more influencing in Portugal and Brazil contrasting with UK and China, although it seems its impact is increasing in UK and China. Nuclear energy contribution has played a null role in Portugal, a punctual role in Brazil and UK, and a negligible one in China. Remaining effects – emission coefficient factor and fossil fuel substitution – have had a marginal impact comparatively to main drivers for all countries.

The results obtained also indicate that, within the different classification of effects considered (i.e. scale, intensity, and structure), common aspects would contribute to reduce overall emissions in spite of developmental stage. Regarding scale effect, for example, increasing attention should be focused on behavioural issues while a joint approach to intensity and structural effects would improve reduction of overall emissions. Although focused separately, interconnectivity amongst effects was considerable and has contributed to reach most accentuated decreases in overall emissions.

In terms of policy implications, the findings of this paper have emphasised that beyond the need to shift towards a renewable energy mix, it is necessary to promote diversification of the energy mix in order to mitigate RES vulnerability to climate variability and, ultimately, to climate change events. They have also emphasised correlation between effects, and the need to address these interconnections at policy level to further improve emission reductions. Furthermore, such an inclusive approach would contribute to promote synergies within the energy sector, regarding energy security, climate change and pollution mitigation goals. Decomposition results have also highlighted the need to extend this approach to focus the increasing importance of behavioural issues in emission reduction.

Thus, the "extended" decomposition approach undertaken has allowed to identify the main drivers for energy- related CO_2 emissions, while promoting a cross-country comparison. It has also contributed to assess the evolution of each effect's behaviour (including nuclear energy) along the considered timeframe of twenty years. As main common emission drivers, energy intensity, affluence and contribution of RES and their inter-linkages constitute areas that require a more immediate action by energy policy decision-makers. Although these areas could be considered transversal to the set of countries featured in this assessment, the results obtained have specified some priorities at country level. For instance, Brazil and Portugal need to focus promptly on issues regarding the improvement of energy efficiency (thereby reducing energy intensity), whereas China and UK need to prioritize issues regarding the weight of non-renewable energy sources in their energy mix. Open-ended nature of the contribution of nuclear energy is still a matter for debate. Further efforts should be developed in determining main CO_2 emissions from a more holistic perspective, by combining, for example, decomposition approach with Life Cycle Assessment (LCA).

Acknowledgements

This research was supported by a Marie Curie International Research Staff Exchange Scheme Fellowship within the 7th European Union Framework Programme, under project NETEP- European Brazilian Network on Energy Planning (PIRSES-GA-2013-612263) and by COMPETE: POCI-01-0145-FEDER-007043 and FCT – Fundação para a Ciência e Tecnologia within the Project Scope: UID/CEC/00319/2013. Support from CNPq is also acknowledged.

References

[1] S. T. Henriques, K. J. Borowiecki, The Drivers of Long-run CO 2 Emissions : A Global Perspective since 1800", Discussion Papers on Business and Economics, University of Southern Denmark, 13/2014.

[2] Peter Mulder and Henri L.F. de Groot, "Energy Intensity across Sectors and Countries: Empirical Evidence 1980–

2005," 2011.

[3] S. G. Banerjee, M. Bhatia, G. E. Azuela, I. Jaques, A. Sarkar, E. Portale, I. Bushueva, N. Angelou, and J. G. Inon, "Global Tracking Framework," p. 289, 2013.

[4] G. R. Timilsina and A. Shrestha, "Transport sector CO2 emissions growth in Asia: Underlying factors and policy options," *Energy Policy*, vol. 37, no. 11, Elsevier, pp. 4523–4539, 2009.

[5] P. Eickemeier, S. Schlömer, E. Farahani, S. Kadner, S. Brunner, I. Baum, and B. Kriemann, "Climate Change 2014 Mitigation of Climate Change Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," 2014.

[6] A. F. Pereira de Lucena, "Uma análise de decomposição das emissões de CO 2 relacionadas ao uso de energia nos setores produtivos brasileiros," in *CADMA- 2º Congresso Acadêmico sobre Meio Ambiente e Desenvolvimento. Área 3: Sociedade e Meio Ambiente*, 2006, pp. 3–11.

[7] Y. Kaya, "Impact of Carbon Dioxide Emission Control on GNP Growth: Interpretation of Proposed Scenarios.," *Pap. Present. to IPCC Energy Ind. Subgroup, Response Strateg. Work. Group, Paris, (mimeo).*, 1990.

[8] International Energy Agency (IEA), "CO2 Emissions from Fossil Fuel Combustion Highlights," Paris, 2014.

[9] T. O. Mahony and J. Dufour, "ScienceDirect Tracking development paths : Monitoring driving forces and the impact of carbon-free energy sources in Spain," *Environ. Sci. Policy*, vol. 50, no. 2007, pp. 62–73, 2015.

[10] B. W. Ang, "Decomposition analysis for policymaking in energy: Which is the preferred method?," *Energy Policy*, vol. 32, no. 9, pp. 1131–1139, 2004.

[11] X. Y. Xu and B. W. Ang, "Index decomposition analysis applied to CO 2 emission studies," *Ecol. Econ.*, vol. 93, pp. 313–329, 2013.

[12] H. Li and Y. Wei, "Is it possible for China to reduce its total CO 2 emissions ?," *Energy*, vol. 83, pp. 438–446, 2015.

[13] S. Voigt, E. De Cian, M. Schymura, and E. Verdolini, "Energy intensity developments in 40 major economies: Structural change or technology improvement?," Elsevier B.V., 2014.

[14] L. Wu, S. Liu, D. Liu, Z. Fang, and H. Xu, "Modelling and forecasting CO 2 emissions in the BRICS (Brazil , Russia , India , China , and South Africa) countries using a novel multi-variable grey model," *Energy*, vol. 79, pp. 489–495, 2015.

[15] A. Lopes, D. Carvalho, C. Henggeler, F. Freire, and C. Oliveira, "A hybrid input e output multi-objective model to assess economic e energy e environment trade-offs in Brazil," *Energy*, vol. 82, pp. 769–785, 2015.

[16] M. Robaina Alves and V. Moutinho, "Decomposition analysis and Innovative Accounting Approach for energy-related CO2 (carbon dioxide) emissions intensity over 1996-2009 in Portugal," *Energy*, vol. 57, pp. 775–787, 2013.

[17] P. Fernández González, M. Landajo, and M. J. Presno, "Multilevel LMDI decomposition of changes in aggregate energy consumption. A cross country analysis in the EU-27," *Energy Policy*, vol. 68, pp. 576–584, 2014.

[18] J. Kaivo-oja, J. Luukkanen, J. Panula-ontto, J. Vehmas, Y. Chen, S. Mikkonen, and B. Auffermann, "Are structural change and modernisation leading to convergence in the CO 2 economy ? Decomposition analysis of China , EU and USA," *Energy*, vol. 72, pp. 115–125, 2014.

[19] G. a. Marrero and F. J. Ramos-Real, "Activity sectors and energy intensity: Decomposition analysis and policy implications for European countries (1991-2005)," *Energies*, vol. 6, no. 5, pp. 2521–2540, 2013.

[20] C. Yao, K. Feng, and K. Hubacek, "Ecological Informatics Driving forces of CO 2 emissions in the G20 countries : An index decomposition analysis from 1971 to 2010," *Ecol. Inform.*, vol. 26, pp. 93–100, 2015.

[21] J. F. Braun, "Working Paper Between a new policy and business as usual EU Energy Policy under the Treaty of Lisbon Rules," 2011.

[22] International Energy Agency (IEA), "CO2 Emissions Statistics," 2013. [Online]. Available: http://iea.org/statistics/topics/CO2emissions.

[23] World Bank, "World Development Indicators (WDI) Tables," 2015. [Online]. Available: www.worldbank.org/tables.

[24] B. W. Ang and F. Q. Zhang, "A survey of index decomposition analysis in energy and environmental studies," *Energy*, vol. 25, no. 12, pp. 1149–1176, Dec. 2000.

[25] International Energy Agency (IEA), "IEA CO2 Emissions from Fuel Combustion, OECD/IEA, Paris, 2015.," 2015. [Online]. Available: http://wds.iea.org/wds/pdf/Worldco2_Documentation.pdf.

[26] P. Fernández González, M. J. Presno, and M. Landajo, "Regional and sectoral attribution to percentage changes in the European Divisia carbonization index," *Renew. Sustain. Energy Rev.*, vol. 52, pp. 1437–1452, 2015.

[27] Y.-J. Zhang and Y.-B. Da, "The decomposition of energy-related carbon emission and its decoupling with economic growth in China," *Renew. Sustain. Energy Rev.*, vol. 41, pp. 1255–1266, 2015.

[28] X. Ouyang and B. Lin, "An analysis of the driving forces of energy-related carbon dioxide emissions in China's industrial sector," *Renew. Sustain. Energy Rev.*, vol. 45, pp. 838–849, 2015.

[29] L. Charlita, D. Freitas, and S. Kaneko, "Decomposition of CO 2 emissions change from energy consumption in Brazil : Challenges and policy implications," *Energy Policy*, vol. 39, no. 3, pp. 1495–1504, 2011.

[30] L. C. Freitas and S. Kaneko, “Decomposing the decoupling of CO2 emissions and economic growth in Brazil,” *Ecol. Econ.*, vol. 70, no. 8, pp. 1459–1469, 2011.
[31] A. Rodríguez and H. Rüstemo, “Environmental Science & Policy Determinants of CO 2 emissions in Brazil and Russia between 1992 and 2011 : A decomposition analysis,” vol. 58, pp. 95–106, 2016.
[32] U. Wachsmann, R. Wood, M. Lenzen, and R. Schaeffer, “Structural decomposition of energy use in Brazil from 1970 to 1996,” *Appl. Energy*, vol. 86, no. 4, pp. 578–587, 2009.
[33] G. P. Hammond and J. B. Norman, “Decomposition analysis of energy-related carbon emissions from UK manufacturing,” *Energy*, vol. 41, no. 1, pp. 220–227, 2012.
[34] M. Landajo, M. J. Presno, and P. Fern, “Tracking European Union CO 2 emissions through LMDI (logarithmic-mean Divisia index) decomposition . The activity revaluation approach ndez Gonz a,” vol. 73, pp. 741–750, 2014.
[35] M. Karmellos, D. Kopidou, and D. Diakoulaki, “A decomposition analysis of the driving factors of CO2 (Carbon dioxide) emissions from the power sector in the European Union countries,” *Energy*, vol. 94, pp. 680–692, 2016.
[36] B. W. Ang, “The LMDI approach to decomposition analysis: A practical guide,” *Energy Policy*, vol. 33, no. 7, pp. 867–871, 2005.
[37] B. Commoner, “A bulletin dialogue on ‘the closing circle’ Response,” *Bull. At. Sci.*, vol. 28, no. 5, pp. 2–41, 1972.
[38] J. P. Ehrlich, Paul R.; Holdren, “Impact of population growth,” *Science (80-.).*, vol. 171, no. 3977, pp. 1212–1217, 1971.
[39] T. H. Kwon, “Decomposition of factors determining the trend of CO2 emissions from car travel in Great Britain (1970-2000),” *Ecol. Econ.*, vol. 53, no. 2, pp. 261–275, 2005.
[40] E. A. Rosa and T. Dietz, “Human drivers of national greenhouse-gas emissions,” *Nat. Publ. Gr.*, no. June, pp. 1–6, 2012.
[41] T. O. Mahony, “Decomposition of Ireland ’ s carbon emissions from 1990 to 2010 : An extended Kaya identity,” *Energy Policy*, vol. 59, pp. 573–581, 2013.
[42] C. Ma and D. I. Stern, “Biomass and China ’ s carbon emissions : A missing piece of carbon decomposition,” vol. 36, pp. 2517–2526, 2008.
[43] B. W. Ang and F. L. Liu, “A New Energy Decomposition Method: Perfect in Decomposition and Consistant in Aggregation,” *Energy*, vol. 26, pp. 537–548, 2001.
[44] A. Baležentis, T. Baležentis, and D. Streimikiene, “The energy intensity in Lithuania during 1995-2009: A LMDI approach,” *Energy Policy*, vol. 39, no. 11, pp. 7322–7334, 2011.
[45] S. T. Henriques and A. Kander, “The modest environmental relief resulting from the transition to a service economy,” *Ecol. Econ.*, vol. 70, no. 2, pp. 271–282, 2010.
[46] T. O’ Mahony, P. Zhou, and J. Sweeney, “The driving forces of change in energy-related CO 2 emissions in Ireland: A multi-sectoral decomposition from 1990 to 2007,” *Energy Policy*, vol. 44, pp. 256–267, 2012.
[47] M. Robaina-Alves and V. Moutinho, “Decomposition of energy-related GHG emissions in agriculture over 1995-2008 for European countries,” *Appl. Energy*, vol. 114, pp. 949–957, 2014.
[48] S. Sorrell, M. Lehtonen, L. Stapleton, J. Pujol, and T. Champion, “Decomposing road freight energy use in the United Kingdom,” *Energy Policy*, vol. 37, no. 8, pp. 3115–3129, 2009.
[49] D. Diakoulaki and M. Mandaraka, “Decomposition analysis for assessing the progress in decoupling industrial growth from CO 2 emissions in the EU manufacturing sector,” vol. 29, pp. 636–664, 2007.
[50] F. Zhang and B. Ang, “Methodological isues in cross-country - region decomposition of energy and environment indicators,” *Energy Econ.*, vol. 23, pp. 179–190, 2001.
[51] B. W. Ang and N. Liu, “Handling zero values in the logarithmic mean Divisia index decomposition approach,” *Energy Policy*, vol. 35, no. 1, pp. 238–246, 2007.
[52] U.S. Energy Information Administration, “International Energy Outlook 2010,” 2010.
[53] International Monetary Fund, “World Economic Outlook - Uneven Growth Short- and Long-Term Factors,” Washington, 2015.
[54] A. M. Dias, A. Teixeira, F. Azevedo, L. Gonçalves, M. D. Guerra, R. R. (coordenação), S. R. (coordenação), and A. A. (diretor), “Relatório do Estado do Ambiente 2013,” 2013.
[55] T. O. Mahony, P. Zhou, and J. Sweeney, “Integrated scenarios of energy-related CO 2 emissions in Ireland : A multi-sectoral analysis to 2020,” *Ecol. Econ.*, vol. 93, pp. 385–397, 2013.
[56] I. Arto and E. Dietzenbacher, “Drivers of the Growth in Global Greenhouse Gas Emissions,” *Environ. Sci. Technol.*, no. 48, pp. 5388–5394, 2014.
[57] A. T. Yalta and H. Cakar, “Energy consumption and economic growth in China : A reconciliation,” *Energy Policy*, vol. 41, pp. 666–675, 2012.
[58] U.S. Energy Information Administration, “China-International energy data and analysis,” 2015.
[59] W. Wang, X. Liu, M. Zhang, and X. Song, “Using a new generalized LMDI (logarithmic mean Divisia index) method to analyze China’s energy consumption,” *Energy*, vol. 67, pp. 617–622, 2014.

[60] M. Roelfsema, M. Den Elzen, N. Höhne, A. F. Hof, N. Braun, H. Fekete, H. Böttcher, R. Brandsma, and J. Larkin, “Are major economies on track to achieve their pledges for 2020 ? An assessment of domestic climate and energy policies,” *Energy Policy*, vol. 67, pp. 781–796, 2014.
[61] ODYSSEE-MURE, “Energy Efficiency Profile : Portugal,” Lisbon, 2012.
[62] P. Appleby, J. Fennema, A. Naumov, M. Schaffer, and R. Christof, “Economic development and the demand for energy : A historical perspective on the next 20 years,” vol. 50, pp. 109–116, 2012.
[63] G. P. Hammond and J. B. Norman, “Decomposition analysis of energy-related carbon emissions from UK manufacturing,” *Energy*, vol. 41, no. 1, pp. 220–227, 2012.
[64] ODYSSEE-MURE, “Energy Efficiency Profile : UK,” London, 2012.
[65] F. P. Lucena, I. V. L. Costa, L. P. P. Nogueira, B. S. M. C. Borba, A. Szklo, R. Schaeffer, P. R. R. Rochedo, D. A. C. Branco, and M. F. H. Ju, “Energy-related climate change mitigation in Brazil : Potential , abatement costs and associated policies,” vol. 49, pp. 430–441, 2012.
[66] International Renewable Energy Agency, “IRENA-GWEC: 30 Years of Policies for Wind Energy- Brazil Market Overview,” 2013.
[67] F. Pereira, D. Lucena, A. Salem, R. Schaeffer, R. Rodrigues, D. Souza, B. Soares, M. Cesar, and I. Vaz, “The vulnerability of renewable energy to climate change in Brazil,” vol. 37, pp. 879–889, 2009.
[68] Federative Republic of Brazil, “Intended Nationally Determined Contribution,” 2015.
[69] R. L. P. Dos Santos, L. P. Rosa, M. C. Arouca, and A. E. D. Ribeiro, “The importance of nuclear energy for the expansion of Brazil’s electricity grid,” *Energy Policy*, vol. 60, pp. 284–289, 2013.
[70] U.S. Energy Information Administration, “United Kingdom-International energy data and analysis,” 2014.
[71] M. Nachmany, S. Fankhauser, T. Townshend, M. Collins, A. Matthews, C. Pavese, and K. Rietig, “The GLOBE Climate Legislation Study,” 2014.
[72] International Renewable Energy Agency, “IRENA-GWEC: 30 Years of Policies for Wind Energy- Portugal Market Overview,” 2011.
[73] E. Union, “Submission by Latvia and the European Commission on behalf of the European Union and its Member States,” vol. 2007, no. September 2013, pp. 1–7, 2015.

Appendix A.

Complete decomposition results by country between 1990 and 2010.

Table A1.
Annual decomposition results 1990-2010 time series for Portugal

Portugal	*Cemf*	*Cffse*	*Cnec*	*Crec*	*Cint*	*Cypc*	*Cpop*	*Ctot*

1990-1991	1,03	1,00	1,00	1,00	0,97	1,05	1,00	1,04
1991-1992	1,01	0,99	1,00	1,04	1,05	1,01	1,00	1,10
1992-1993	0,99	1,01	1,00	0,98	1,01	0,98	1,00	0,97
1993-1994	1,00	1,00	1,00	0,99	1,02	1,01	1,00	1,01
1994-1995	0,97	1,00	1,00	1,03	1,06	1,04	1,00	1,10
1995-1996	1,01	1,00	1,00	0,97	0,96	1,03	1,00	0,97
1996-1997	0,99	1,00	1,00	1,01	1,01	1,04	1,00	1,04
1997-1998	1,01	0,98	1,00	1,03	1,03	1,05	1,00	1,10
1998-1999	1,01	1,00	1,00	1,04	1,03	1,04	1,00	1,12
1999-2000	0,99	1,00	1,00	0,97	0,97	1,03	1,01	0,97
2000-2001	1,01	0,99	1,00	0,99	0,99	1,01	1,01	1,00
2001-2002	1,01	1,00	1,00	1,02	1,03	1,00	1,01	1,07
2002-2003	0,99	1,00	1,00	0,96	0,98	0,98	1,01	0,92
2003-2004	0,99	1,00	1,00	1,01	1,01	1,01	1,01	1,03
2004-2005	1,00	1,00	1,00	1,02	1,02	1,00	1,00	1,04
2005-2006	0,98	1,00	1,00	0,98	0,92	1,01	1,00	0,90
2006-2007	1,02	0,99	1,00	0,96	1,00	1,02	1,00	0,99
2007-2008	1,00	0,99	1,00	1,00	0,97	1,00	1,00	0,95
2008-2009	0,99	1,01	1,00	0,99	1,02	0,97	1,00	0,98
2009-2010	1,00	0,97	1,00	0,95	0,96	1,02	1,00	0,90
1990-2010	0,99	0,95	1,00	0,94	0,98	1,30	1,06	1,19

Table A2.
Annual decomposition results 1990-2010 time series for United Kingdom (UK)

UK	***Cemf***	***Cffse***	***Cnec***	***Crec***	***Cint***	***Cypc***	***Cpop***	***Ctot***
1990-1991	1,00	1,00	1,00	1,00	1,05	0,98	1,00	1,03
1991-1992	1,01	0,99	0,99	1,00	0,99	1,01	1,00	0,99
1992-1993	0,98	0,98	0,98	1,00	0,98	1,03	1,00	0,96

1993-1994	0,99	0,99	1,00	1,00	0,96	1,04	1,00	0,99
1994-1995	1,01	0,99	1,00	1,00	0,97	1,03	1,00	1,00
1995-1996	1,00	0,98	1,00	1,00	1,01	1,03	1,00	1,03
1996-1997	1,00	0,99	0,99	1,00	0,94	1,04	1,00	0,95
1997-1998	0,99	1,00	1,00	1,00	0,98	1,03	1,00	1,00
1998-1999	0,99	0,99	1,01	1,00	0,97	1,03	1,00	0,98
1999-2000	1,00	1,00	1,01	1,00	0,96	1,04	1,00	1,02
2000-2001	1,01	1,01	0,99	1,00	0,98	1,02	1,00	1,01
2001-2002	1,00	0,99	1,00	1,00	0,95	1,02	1,00	0,97
2002-2003	0,99	1,01	1,00	1,00	0,98	1,03	1,00	1,02
2003-2004	1,00	1,00	1,01	1,00	0,97	1,02	1,00	1,00
2004-2005	1,00	1,00	1,00	1,00	0,98	1,02	1,01	1,00
2005-2006	1,00	1,01	1,01	1,00	0,96	1,02	1,01	1,00
2006-2007	1,01	0,99	1,01	1,00	0,93	1,03	1,01	0,98
2007-2008	1,01	0,99	1,01	0,99	1,00	0,98	1,01	0,99
2008-2009	1,01	0,99	0,97	1,00	0,98	0,95	1,01	0,91
2009-2010	1,00	1,00	1,01	1,00	1,01	1,01	1,01	1,04
1990-2010	0,99	0,91	1,00	0,97	0,63	1,43	1,09	0,86

Table A3.
Annual decomposition results 1990-2010 time series for Brazil

Brazil	***Cemf***	***Cffse***	***Cnec***	***Crec***	***Cint***	***Cypc***	***Cpop***	***Ctot***
1990-1991	1,01	1,01	1,00	1,01	1,00	1,00	1,02	1,05
1991-1992	1,00	1,00	1,00	1,02	1,02	0,98	1,02	1,02
1992-1993	1,01	1,00	1,00	1,01	0,98	1,03	1,02	1,05

1993-1994	1,00	1,00	1,00	1,00	1,00	1,04	1,02	1,05
1994-1995	1,00	1,00	0,99	1,03	0,99	1,03	1,02	1,06
1995-1996	1,01	1,00	1,00	1,03	1,03	1,01	1,02	1,09
1996-1997	1,00	1,00	1,00	1,01	1,02	1,02	1,02	1,05
1997-1998	1,00	1,00	1,00	1,01	1,02	0,99	1,02	1,04
1998-1999	1,00	1,00	1,00	1,00	1,02	0,99	1,01	1,02
1999-2000	1,01	1,00	1,00	1,02	0,96	1,03	1,01	1,03
2000-2001	1,00	1,00	0,98	1,03	1,00	1,00	1,01	1,03
2001-2002	1,00	1,00	1,00	0,97	1,00	1,01	1,01	0,99
2002-2003	1,00	1,00	1,00	0,96	1,00	1,00	1,01	0,98
2003-2004	1,00	1,00	1,01	1,00	1,00	1,04	1,01	1,05
2004-2005	1,01	1,00	1,00	0,99	0,99	1,02	1,01	1,02
2005-2006	0,98	1,00	0,99	0,99	1,00	1,03	1,01	1,00
2006-2007	1,00	1,00	1,00	0,98	1,00	1,05	1,01	1,04
2007-2008	1,01	1,00	1,00	1,00	1,00	1,04	1,01	1,06
2008-2009	1,00	0,99	1,00	0,98	0,97	0,99	1,01	0,94
2009-2010	0,99	1,00	1,00	1,04	1,03	1,07	1,01	1,15
1990-2010	1,03	0,98	0,98	1,06	1,03	1,40	1,30	1,99

Table A4.
Annual decomposition results 1990-2010 time series for China

China	***Cemf***	***CFFse***	***Cnec***	***Crec***	***Cint***	***Cypc***	***CPOP***	***Ctot***
1990-1991	1,09	1,00	1,00	0,99	0,90	1,07	1,01	1,04
1991-1992	0,99	1,00	1,00	1,01	0,91	1,12	1,01	1,03
1992-1993	0,99	1,00	1,00	1,02	0,93	1,12	1,01	1,06

1993-1994	1,00	1,00	1,00	1,01	0,93	1,11	1,01	1,06
1994-1995	0,99	1,00	1,00	1,02	0,97	1,09	1,01	1,08
1995-1996	1,01	1,00	1,00	1,01	0,94	1,08	1,01	1,04
1996-1997	1,01	0,99	1,00	1,00	0,92	1,08	1,01	1,00
1997-1998	0,94	1,00	1,00	1,00	0,94	1,06	1,01	0,95
1998-1999	0,97	1,00	1,00	1,00	0,95	1,06	1,01	0,99
1999-2000	0,96	1,00	1,00	1,01	0,97	1,08	1,01	1,02
2000-2001	1,00	1,00	1,00	1,00	0,95	1,07	1,01	1,02
2001-2002	0,99	1,00	1,00	1,01	0,97	1,08	1,01	1,06
2002-2003	1,05	1,00	1,00	1,03	1,04	1,09	1,01	1,23
2003-2004	1,00	1,00	1,00	1,02	1,04	1,09	1,01	1,17
2004-2005	1,00	1,00	1,00	1,01	0,97	1,10	1,01	1,09
2005-2006	1,00	1,00	1,00	1,01	0,97	1,12	1,01	1,10
2006-2007	1,00	1,00	1,00	1,00	0,93	1,13	1,01	1,05
2007-2008	1,00	1,00	1,00	1,00	0,95	1,09	1,01	1,04
2008-2009	1,00	1,00	1,00	1,01	0,99	1,08	1,01	1,08
2009-2010	0,96	1,00	1,00	1,01	1,00	1,10	1,00	1,07
1990-2010	0,94	0,99	0,99	1,18	0,42	5,76	1,18	3,12